sustainability

MDPI

Article

Genetic Algorithm for Embodied Energy Optimisation of Steel-Concrete Composite Beams

Alex H. Whitworth [1] and Konstantinos Daniel Tsavdaridis [2,*]

[1] WSP in the UK, WSP House, 70 Chancery Lane, London WC2A 1AF, UK; Alex.Whitworth@wsp.com
[2] School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK
* Correspondence: K.Tsavdaridis@leeds.ac.uk; Tel.: +44(0)-113-343-2299

Received: 27 January 2020; Accepted: 10 April 2020; Published: 13 April 2020

Abstract: The optimisation of structural performance is acknowledged as a means of obtaining sustainable structural designs. A minimisation of embodied energy of construction materials is a key component in the delivery of sustainable future designs. This study attempts to understand the relationship between embodied energy and structural form of composite floor plates for tall buildings, and how this form can be optimised to minimise embodied energy. As a search method based upon the principles of genetics and natural selection, genetic algorithms (GA) have previously been used as novel means of optimising composite beams and composite frames for cost and weight objective functions. Parametric design models have also been presented as optimisation tools to optimise steel floor plates for both cost and embodied carbon. In this study, a Matlab algorithm is presented incorporating MathWorks global optimisation toolbox GA and utilising Eurocode 4 design processes to optimise a composite beam for five separate objective functions: maximise span length; minimise beam cross-section; minimise slab depth; minimise weight; minimise deflected shape for each of the objective functions. Candidate designs are to be assessed for embodied energy to determine individual relationships. This study shows that it is possible to reduce the embodied energy of steel–concrete composite beams by genetic algorithm optimisation whilst remaining compliant to given design codes.

Keywords: steel-concrete composite beams; embodied energy; genetic algorithm; optimisation; steel floor plates; weight reduction

1. Introduction

Researchers are focusing on optimising the material efficiency of structures and structural systems [1–5] as well as on the performance of structures and buildings specifically to wind and seismic actions by minimising weight and control capacity [6–11], in order to avoid using redundant material, thus increasing the stiffness over weight ratio without compromising their capacity. However, the optimisation process can be time and resource intensive when it is done with traditional methods, thus in recent years advanced computational tools have been employed to carry out effective material distribution for structures, such as the shape and topology optimisation techniques [12–15], technologies previously used in aeronautical and automotive engineering where material savings is of ultimate importance for the performance of the shuttle and vehicles. More recently, another form of optimisation is employing large data sets, developed by advanced computational and parametric studies, which optimise the right combination of parameters through the large volume of data to be used in a structural system. A simple and reliable algorithm is the genetic algorithm (GA) [16] which has previously been used to optimise composite beams [17–19] and composite frames [20] for cost and weight objective functions. Parametric design models [21,22] have also been presented as a novel optimisation tool to optimise steel floor plates for both cost and embodied carbon. When compared to traditional engineering design practice, a much greater quantity of candidate designs can be generated in the same timeframe, providing a new way of informing designers of an optimal solution.

Utilising GA as an optimiser for civil engineering structures has featured in previous studies. Particularly for steel-concrete composite structures, GA has been employed previously for cost optimisation by Panchal [17], Alanka and Chaudhary [18], and Senouci and Ansari [19]. GA has also been employed to optimise composite frames for weight by Artar and Daloglu [20]. Eleftheriadis, Dunant, Drewniok, Rogers-Tizard, and Kyprianou [21,22] have experimented with the use of parametric design models to optimise steel floor plates to minimise for cost and carbon footprint. However, the optimisation of steel-concrete composite beams for embodied energy content by the utilisation of GA is yet to be undertaken.

In this study, a MATLAB algorithm is presented incorporating MathWorks global optimisation toolbox GA [23] and utilising Eurocode 4 [24] design processes to optimise a composite beam for five separate objective functions: maximise span length; minimise beam cross-section; minimise slab depth; minimise weight; minimise deflected shape for each of these objective functions. Candidate designs are to be assessed for embodied energy [10] to determine individual relationships.

The following section describes the current practice into the optimisation of steel-concrete composite beams, the genetic algorithm as a means of optimisation, and the importance of this work in a boarder context. Section 3 defines both the structural design as well as the embodied energy quantification processes implemented in this study. Section 4 describes how the GA function of MATLAB Global optimisation toolbox is implemented. In Section 5, the outcomes of this optimisation are reviewed and discussed, and the implications of this work are summarised together with the next steps of the research area.

2. Optimising Steel-Concrete Composite Structures

2.1. The Genetic Algorithm

The Genetic Algorithm (GA) is a metaheuristic search method based on the process of natural selection [16]. Instead of the evolution of organic species in response to external conditions, a GA is a method in which the fitness of candidate designs is assessed against user-defined conditions and developed to produce a design that fits these conditions best. In operation, the GA utilises the following five steps [25]:

1. From input parameters, populations of candidate solutions are randomly generated;
2. The performance of a candidate solution within the population are determined against defined fitness functions;
3. Repetition; selection of pairs of parent solutions, random crossover to produce candidate solutions, and mutation of offspring solutions;
4. Form a new population with these offspring solutions;
5. Repeat this process until an optimal solution has been returned.

2.2. Aims of this Study

This study is the first item of work within a wider research project exploring the optimisation of structural floor plates for tall building structures. The specification of steel-concrete composite beams is a common element of such floor plates, and consequently, it is the consideration of a beam element that is the primary focus of this study, i.e., to determine how variations amongst the properties of the steel-concrete composite beam impact upon the embodied energy content of the structure. For this study, the following objective functions for optimisation are approached:

- Minimisation of the universal beam (UB) section—Objective function 1
- Minimisation of depth of the concrete slab (d_{slab})—Objective function 2

- Minimisation of overall weight of the composite beam—Objective function 3
- Maximisation of the span length of the composite beam—Objective function 4
- Minimisation of the deflection of the composite beam—Objective function 5

MATLAB is used to assess the ultimate (ULS) and serviceability (SLS) limit states of the composite beam in accordance with design codes. It is proposed to utilise the MATLAB app Global Optimisation Toolbox [23] GA optimiser to tackle these objective functions.

The learning outcomes of this study are to be used to further refine the optimisation process for composite beams embodied energy content, and to progress to the optimisation of more complicated composite grid and floor plate structures.

3. Methodology for Structural Design and Life Cycle Energy Assessment

3.1. Structural Form

The structure in question is a single steel-concrete composite beam, comprising a universal I beam section, profiled steel sheeting, shear connectors, and a concrete slab with steel mesh reinforcement (Figure 1). This form of construction is common for a variety of building types, including high rise buildings. The beam is assumed to be simply supported (Figure 2) and can be considered as either a primary beam spanning between two columns, or a secondary beam spanning between other beams.

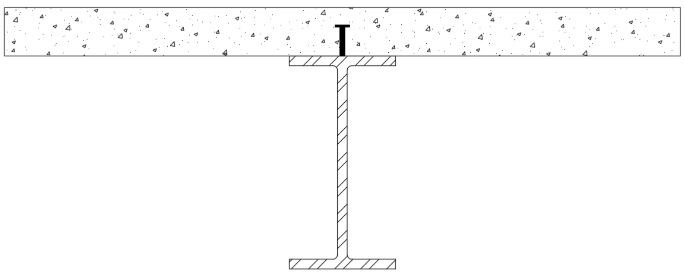

Figure 1. Typical steel-concrete composite beam section.

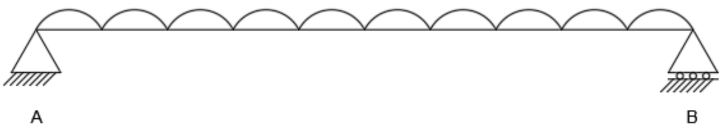

Figure 2. Simple supported beam.

3.2. Actions upon the Structure

With the omission of columns and lateral stability systems, only load cases in a vertical direction are to be considered for this work. These are for actions on the structure during the construction stage, and during the composite stage after the curing of the concrete slab. Calculation of both permanent and variable actions are in kN/m^2. For the construction stage, permanent action g_k is calculated as the sum of both the steel cross-section and the profiled steel decking. Variable action q_k is the sum of the construction loading and the wet self-weight of the concrete slab. For the composite stage, permanent action is calculated as the sum of the steel cross-section, profiled steel sheeting, dry self-weight of the concrete slab, and an assumed loading for finishes. Variable action is taken as 2.5kN/m^2 for a general use office area above ground level [26]. The greatest values for both g_k and q_k are taken as governing and taken forward to calculating a combination of actions (F_d) in accordance to Equations (6) and (10) from Eurocode 0 [27]. Partial factors of safety for the permanent action γ_g is taken as 1.35, for variable action γ_q is taken as 1.5 from the UK National Annexe to Eurocode – Basis of Structural Design BS EN 1990:2002+A1:2005 [28].

3.3. Ultimate Limit State Verification

With the design combination of actions calculated, this is worked into design moment M_{Ed} and shear force V_{Ed} acting upon the structure, where:

$$M_{y,Ed} = \frac{F_d L^2}{8} \tag{1}$$

$$V_{Ed} = \frac{F_d L}{2} \tag{2}$$

Next, design checks in accordance with Eurocode 4: Design of Composite Steel and Concrete Structures BS EN 1994-1-1:2004 [24] are undertaken. Beginning with determining moment capacity for full shear connection $M_{pl,Rd}$, where:

$$M_{pl,Rd} = N_{pl,a}\left[\frac{h_a}{2} + d_{slab} - \frac{N_{pl,a}}{N_{c,slab}} \times \frac{h_c}{2}\right] \tag{3}$$

$$N_{pl,a} = \frac{f_y A_a}{\gamma_{M0}} \tag{4}$$

$$N_{c,slab} = f_{cd} b_{eff} h_c \tag{5}$$

$$b_{eff} = b_o + \sum b_{ei} \tag{6}$$

$$b_{ei} = \frac{L_e}{8} \leq b_i \tag{7}$$

Design moment capacity verified by:

$$\frac{M_{y,Ed}}{M_{pl,Rd}} \leq 1.0 \tag{8}$$

Assuming circumstances where the shear connection is not full, shear connection resistance P_{Rd} and degree of shear connection R_q are calculated, where P_{Rd} is:

$$P_{Rd} = the\ minimum \tag{9}$$

$$P_{Rd} = \frac{0.8 f_u \pi \varnothing^2/4}{\gamma_v} \tag{10}$$

$$P_{Rd} = \frac{0.29\alpha\varnothing^2\sqrt{f_{ck}E_{cm}}}{\gamma_v} \tag{11}$$

$$\alpha = 0.2\left(\frac{h_{sc}}{\varnothing} + 1\right) for\ 3 \leq \frac{h_{sc}}{\varnothing} \leq 4 \tag{12}$$

$$\alpha = 1.0\ for\ \frac{h_{sc}}{\varnothing} > 4 \tag{13}$$

and where R_q is;

$$R_q = nr\ of\ connectors \times P_{Rd} \tag{14}$$

Degree of shear connection verified by:

$$\frac{R_q}{N_{pl,a}} \leq 1.0 \tag{15}$$

With the minimum required shear connection also calculated:

$$R_{q,min} \geq 1 - \left(\frac{355}{f_y}\right)(0.75 - 0.03L_e) \geq 0.4 \tag{16}$$

With the determination of partial shear connection, corresponding moment capacity for partial shear M_{Rd} can be determined.

$$M_{Rd} = M_{pl,a,Rd} + \left(M_{pl,Rd} - M_{pl,a,Rd}\right)R_{q,min} \tag{17}$$

$$M_{pl,a,Rd} = f_{yd}W_{pl,y} \tag{18}$$

Moment capacity verified by:

$$\frac{M_{y,Ed}}{M_{Rd}} \leq 1.0 \tag{19}$$

Resistance to vertical shear $V_{pl,Rd}$ considers the steel section only, and therefore is calculated in accordance with Eurocode 3: Design of Steel Structures BS EN 1993-1-1 [29], where:

$$V_{pl,Rd} = V_{pl,a,Rd} = \frac{A_v\left(f_y/\sqrt{3}\right)}{\gamma_{M0}} \tag{20}$$

$$A_v = A - 2bt_f + t_f(t_w + 2r) \; but \; not \; less \; than \; \acute{\eta}h_w t_w \tag{21}$$

Vertical shear capacity verified by:

$$\frac{V_{Ed}}{V_{pl,Rd}} \leq 1.0 \tag{22}$$

Finally, in accordance with Eurocode 2: Design of Concrete Structures BS EN 1992-1-1 [30] the transverse reinforcement within the slab can be designed, and the crushing of the concrete strut can be checked. For reinforcement design:

$$\frac{A_{sf}}{s_f} > \frac{V_{Ed}d_{slab}}{f_{yd}cot\theta_f} \tag{23}$$

$$f_{yd} = \frac{f_y}{\gamma_s} \tag{24}$$

$$for \; compression \; flanges, \; 26.5^{\circ} \leq \theta_f \leq 45^{\circ} \tag{25}$$

$$V_{Ed} = \frac{R_q}{2d_{slab}\Delta x} \tag{26}$$

This calculation returns the minimum required cross-sectional area per m of slab. An actual cross-sectional area of reinforcement is provided in accordance with manufacturer's data [31]. Crushing of the concrete strut check is undertaken according to:

$$V_{Ed} \leq \nu f_{cd} sin\theta_f cos\theta_f \tag{27}$$

$$\nu = 0.6\left[1 - \frac{f_{ck}}{250}\right] \tag{28}$$

3.4. Serviceability Limit State Verification

For determining the deflected shape of the structure, first, the following assumptions are made:

- At the construction stage, the beam alone is assumed to have insufficient resistance to lateral-torsional buckling and will be fully propped, thus for this scenario, there is no deflection of the beam.

- The beam is assumed to be an internal beam; therefore, relative humidity is assumed as 50%.
- It is assumed that the cement used for the slab is normal hardening, thus class = N.

To begin, owing to the concrete component of the structure, the creep coefficients are determined from these input assumptions using Figure 3.1 of Eurocode 2: Design of Concrete Structures BS EN 1992-1-1 [16] to determine coefficients for concrete with 1-day and 28-day strengths. Shrinkage is determined by calculating the total shrinkage strain ε_{cs} where;

$$\varepsilon_{cs} = \varepsilon_{cd} + \varepsilon_{ca} \tag{29}$$

Basic drying shrinkage strain $\varepsilon_{\mathrm{cd}}$ is determined by:

$$\varepsilon_{cd} 0.85\left[(220 + 110\alpha_{ds1})e\left(-\alpha_{ds2}\frac{f_{cm}}{f_{cm0}}\right)\right]\beta_{RH} \tag{30}$$

$$\beta_{RH} = \left[1 - \left(\frac{RH}{RH_0}\right)^3\right] \tag{31}$$

Autogenous shrinkage strain is determined by:

$$\varepsilon_{ca} = 2.5(f_{ck} - 10mpa) \tag{32}$$

For the composite section, four conditions contribute to the deflected shape of the structure; short term loading, permanent loading, creep, and shrinkage primary effects. The effective flexural stiffness of the composite section is calculated by the general Equation (33):

$$EI_L = E_a I_A + E_L I_c + \frac{E_a A_a E_L A_c}{E_a A_a + E_L I_c} a^2 \tag{33}$$

where:

$$EI_L = EI_0, EI_P, EI_S \tag{34}$$

When:

$$for\ EI_0,\ E_L = E_0 = \frac{E_{cm}}{1} \tag{35}$$

$$for\ EI_P, E_L = E_P = \frac{E_{cm}}{1 + 1.10\varphi_{(t,t0)}} \tag{36}$$

$$for\ EI_S, E_L = E_S = \frac{E_{cm}}{1 + 0.55\varphi_{(t,to)}} \tag{37}$$

Next, deflections can be calculated using general formula:

$$\delta = \frac{5}{384}\frac{e_d L^4}{EI_L} \tag{38}$$

$$\delta_{Total} = \delta_1 + \sum \delta_{2,i} \tag{39}$$

where deflections are due to permanent actions δ_1:

$$e_d = bayspace\left(\sum g_k\right) \tag{40}$$

where deflections are due to variable actions $\delta_{2.1}$:

$$e_d = bayspace\psi_1 q_k \tag{41}$$

where deflections are due to creep under the semi-permanent value of variable actions $\delta_{2.2}$:

$$e_d = bayspace(g_k + \psi_2 q_k) \tag{42}$$

where deflections are due to shrinkage $\delta_{2.3}$:

$$\delta_{2.3} = \frac{1}{8}\frac{M_{cs}L^2}{EI_S} \tag{43}$$

$$M_{cs} = N_{cs}a_c \tag{44}$$

$$a_c = \frac{E_a A_a}{E_a A_a + E_S A_c} \tag{45}$$

$$N_{cs} = \varepsilon_{cs} E_S A_c \tag{46}$$

Deflections must be within allowable limits, as the final checks for SLS for total deflection due to permanent action, variable action, creep and shrinkage:

$$\delta_{Total} \leq \frac{L}{250} \tag{47}$$

For total variable action, creep and shrinkage:

$$\delta_{Var} \leq \frac{L}{360} \tag{48}$$

3.5. Quantification of Embodied Energy

Candidate designs that meet the criterion for ULS and SLS verification will be subject to quantification of embodied energy. Owing to the simple nature of the structure, operational energy is omitted from the whole life assessment, and only the initial embodied energy EE_i of the structure will be quantified as per Equation (49) [32].

$$EE_i = \sum m_i M_i + E_c \tag{49}$$

where M_i is the quantity of material (i), M_i is the cradle to gate energy content of the material (i) per unity quantity, and E_c is the energy used on-site for construction. As the form of the beam under assessment is not variable (i.e., a single simply supported composite beam), the energy consumption for construction is assumed to be constant, and therefore is omitted from the assessment. Similarly, energy consumption for the transport of materials to the site is assumed to be constant, and therefore is also omitted from assessment [32].

The Inventory of Carbon & Energy (ICE) [33] is the most well-documented database source of energy constants for materials up to date. The boundary conditions for global values from ICE for the components of the structure consider energy embodied from cradle to gate (i.e., energy to extract raw material), and all processes to produce construction products up to, but not including transport to site.

Material quantities M_i is to be calculated by the specific component geometries of the candidate designs. For simplification, quantified components are to be limited to the steel universal beam, steel shear connectors, profiled steel sheeting, reinforcing steel, and slab concrete. Supporting columns and connections are assumed to be constant for all candidate designs, and therefore can be omitted from the assessment.

As a simple quantification of embodied energy in terms of total energy content in M_J of the structure, owing to the simplicity of the structure under analysis, it was reasonable to adopt energy per weight as the unit of quantification. It is anticipated that as this work progresses to more complex floor plate structures, it may be more appropriate to utilise more functional units for quantification.

A flowchart of the design and embodied energy quantification processes can be seen in Figure 3.

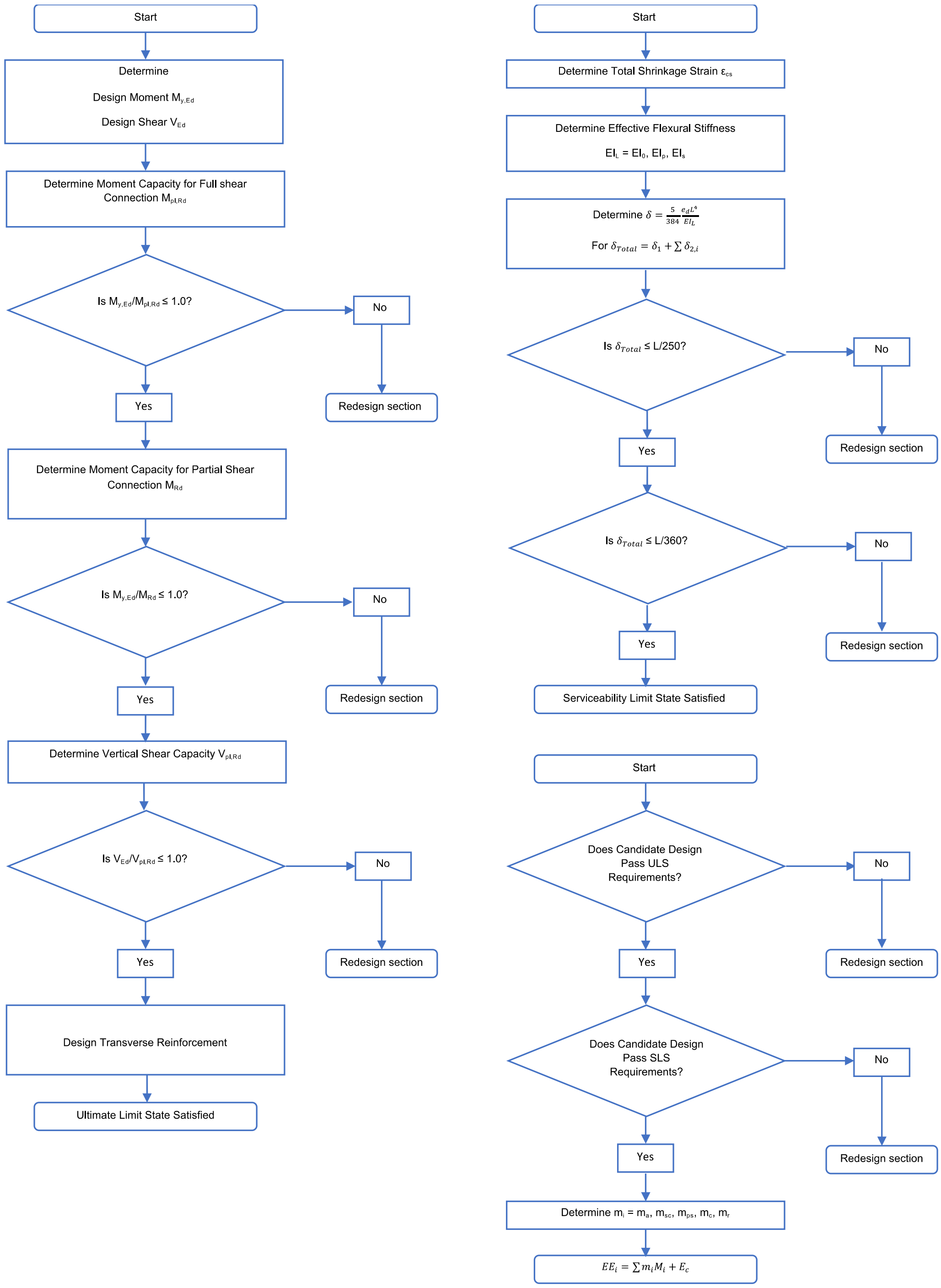

Figure 3. Design and embodied energy quanitification processes.

4. MATLAB Scripts for Optimisation

4.1. General MATLAB Script for Structural Design and Life Cycle Energy Assessment

To optimise the stated objective functions, a MATLAB script was assembled to enable the processes denoted in Section 2 to be undertaken and incorporated with the GA optimiser within MATLAB Global Optimisation Toolbox.

Part 1—Determines the combined actions F_d in accordance to Equations (6.10) of Eurocode 0. F_d is calculated applied to the overall floor area supported by the beam, as floor area is required as an input for later functions. A dedicated MATLAB function is utilised for this purpose. Design moment M_{Ed}, and design shear V_{Ed}, according to Equations (1) and (2) from Section 3.2 are also calculated in the part of the script.

Part 2—Ultimate limit state verification determines the processes for verification of moment capacity, shear capacity, design of transverse reinforcement and crushing of the concrete strut stated within Section 3.3 (Equations (3)–(25)).

Part 3—Serviceability limit state verification determines combined deflections due to permanent actions, variable actions, creep effects and shrinkage stress in accordance with Section 3.4 (Equations (26)–(40)). Checks of allowable deflection areas also undertaken (Equations (41) and (42)).

Part 4—Embodied energy quantification determines the number of materials in terms of kg from calculated volumes or areas. These are multiplied by materials factors and the results totalled in accordance with Section 3.5 (Equation (49)).

4.2. Implementing MATLAB Global Optimisation Toolbox GA

To implement the GA optimiser within MATLAB Global Optimisation Toolbox, firstly the objective function needs to be presented as a MATLAB function. This requires establishing the respective general equation to determine the objective function, the corresponding parameters and corresponding variables. This function when saved is called upon as the fitness function or FitFcn within the GA script.

The GA script can then be constructed with MATLAB. To begin, the constants of the fitness function should be listed and assigned values. Next, the remaining components for the GA should be defined. First, the fitness function should be called upon, and all variables (xi) and parameters of this function should be included. Next, the GA number of variables (nvars) within the fitness function needs to be defined for the GA program. Next, the lower (lb) and upper (ub) bounds of the variables need to be included. These bounds apply a constraint upon the respective script by limiting the range of variables in line with the feasible variable limits. For multiple variables, these limits should be vectorised like so:

$$[lb_1, lb_2, lb_i \ldots] \tag{50}$$

Next, the optimisation options (optimoptions) should be defined. This includes selecting the GA optimiser, establishing the number of generations, setting the stopping criteria of the program, and plotting of outputs. Finally, these components are assembled in the following order:

```
[x,fval] = ga(FitFcn,nvars,[],[],[],[],lb,ub,[],options);
```

where x returns the variable values for the optimised objective function fval. Upon construction of this script, the process is ready to be initialised.

5. Optimisation of a Steel-Concrete Composite Beam

5.1. Minimisation of the Universal Beam Section—Objective Function 1

To begin, the structural design script was given an initial candidate design to establish benchmarks for design moment M_{Ed}, as well as an outputted, embodied energy content. This was done with the following components:

- A 305 × 102 × 25 universal beam with a span length of 6.0m, and bay spacing of 3.0m;
- A 130 mm deep C25/30 concrete slab cast upon;
- COMFLOR® 60 [34] profiled steel sheeting, with SMD19105 shear connectors [35].

The structure passes all ULS and SLS requirements and the energy output of this script was a total of 23493.6 MJ for the entire structure. A breakdown of the material contributions to this embodied energy quantification can be seen in Table 1. With an M_{Ed} output of 119.4 kNm, the moment capacity for full shear connection $M_{pl,Rd}$ output was calculated as 257.8 kNm. In accordance with Equation (8), the check value was 0.46, less than half the check value of 1.0, implying reduction of the UB is achievable.

To minimise the UB section, the GA process was introduced to minimise the depth of the section (ha). First, a fitness function ha_function was written in MATLAB, based upon Equation (3) rearranged to make ha the subject.

$$h_a = \left(\frac{2M_{pl,Rd}}{N_{pl,a}}\right) - 2d_{slab} + \left(\frac{N_{pl,a}h_c}{N_{c,slab}}\right) \tag{51}$$

Production of both the fitness function and GA script gives the following:

```
function ha = ha_function(x, Npla, dslab, NcSLAB, hc)
ha = ((2*(x*10^3))/Npla)-(2*dslab)+((Npla*hc)/NcSLAB);
end
%
%Genetic Algorithm Script for Objective Function 1 - Minimise Universal
%Beam Section.
%
clc, clear, clear all
%
%Define Parameters
hc = 70;
dslab = 130;
Npla = 987.25;
NcSLAB = 1487.5
%Define GA Components
FitFcn = @(x)ha_function(x,Npla,dslab,NcSLAB,hc);
nvars = 1;
lb = 120;
ub = 257.79;
options = optimoptions('ga','Generations',50,...

'MaxStallGenerations',Inf,'PlotFcn',@gaplotbestf);
[x,fval] =ga(FitFcn,nvars,[],[],[],[],lb,ub,[],options);
x
fval
```

For the fitness function, $M_{pl,Rd}$ was set as the variable (x), where other parameters were retained as constants. The GA program calls upon ha_function as the required fitness function. The lower bound for $M_{pl,Rd}$ was set to M_{Ed} rounded to the nearest whole number, to constrain the GA to prevent it from determining a depth of beam that would fail ULS checks. The upper bound for $M_{pl,Rd}$ was set to the computed $M_{pl,Rd}$ of the initial candidate design. This was to provide a practical upper bound that would prevent a solution having a depth greater than the initial candidate design. With a single variable, nvars was set to 1. Finally, options were set to give a run of 50 generations with MATLAB default population sizes of 50. A stopping criterion of infinite generations (MaxStallGenerations) was also included to ensure convergence during test runs of the script. This option was included for completeness, however, was overridden by setting generations to 50. Finally, the best and mean outputs (fval) per generation were plotted against their respective generation (Figure 4) to visualise the convergence of the GA to a solution.

For this objective function, convergence upon a solution occurred after seven generations, giving a minimised ha of 29.3 mm. This was a depth smaller than the stock blue book sections and is unfeasible for the remaining design checks. To determine a solution that passes the ULS and SLS criteria, sections were manually cycled through until the minimum UB section of a 203 × 102 × 32 section was selected for assessment with the same span length and concrete slab depth as the initial candidate design. The total initial embodied energy of this revised design was 22367.5 MJ, a 4.8% reduction compared to the initial candidate design. A breakdown of material contribution to this embodied energy quantification is included in Table 1.

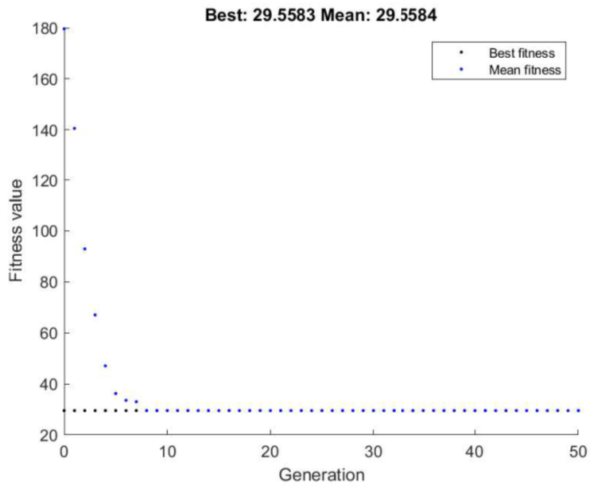

Figure 4. MATLAB plot of Objective function 1.

5.2. Minimisation of Depth of the Concrete Slab—Objective Function 2

This optimisation utilised the same span length and UB section as the initial candidate design. To minimise the concrete slab depth, the GA process was introduced again, however requiring a new fitness function to operate. The fitness function dslab_function was written in MATLAB, also based upon Equation (3), this time rearranged to make d_{slab} the subject.

$$d_{slab} = \left(\frac{M_{pl,Rd}}{N_{pl,a}}\right) - \left(\frac{h_a}{2}\right) + \left(\frac{N_{pl,a} h_c}{2N_{c,slab}}\right) \tag{52}$$

Production of both the fitness function and GA script gives the following:

```
function dslab = dslab_function(x,Npla,NcSLAB,ha,hc)
dslab=((x*10^3)/Npla)-(ha/2)+((Npla*hc)/(2*NcSLAB));
end
%Genetic Algorithm Script for Objective Function 2 - Minimise depth of
%concrete slab.
%
clc, clear, clear all
%
%Define Parameters
hc = 70;
ha = 308.7;
Npla = 987.25;
NcSLAB = 1487.5
%Define GA Components
FitFcn = @(x)dslab_function(x,Npla,NcSLAB,ha,hc);
nvars = 1;
lb = 120;
ub = 257.79;
options = optimoptions('ga','Generations',10,...

'MaxStallGenerations',Inf,'PlotFcn',@gaplotbestf);
[x,fval] =ga(FitFcn,nvars,[],[],[],[],lb,ub,[],options);
x
fval
```

As with objective function 1, $M_{pl,Rd}$ was set as the variable (x), and the remaining parameters retained as constants. The GA program called upon dslab_function as the required fitness function. Lower and upper bounds for $M_{pl,Rd}$ were the same as for objective function 1 as the benchmark span and beam conditions from the initial candidate design were still valid. With a single variable, nvars was again set to 1. For this objective function, the MATLAB population size of 50 was retained. Initially the number of generations was kept at 50, however, as convergence occurred within 5 generations, this reduced to 10 to enable the convergence to be better graphically visualised (Figure 5).

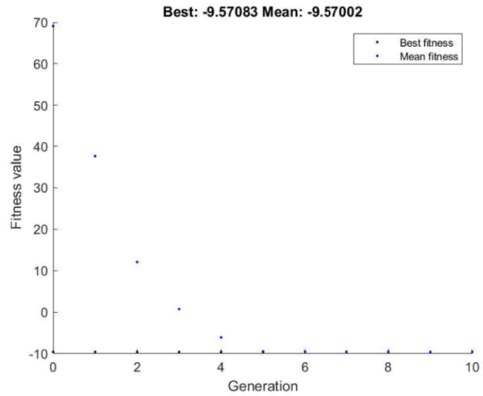

Figure 5. MATLAB plot of objective function 2.

Upon convergence, the GA gave a minimes d_{slab} of −9.57. Numerically this follows Equation (51) accurately, however reaping a negative value is an unfeasible design. To determine a feasible solution, the shallowest slab depth in accordance with manufacturer information [34] of 110 mm was run along with the initial candidate design span length and UB section through the structural design script. This structure passed both ULS and SLS criteria and returned a total initial embodied energy of 22534.6 MJ, a 4.1% reduction of embodied energy compared to the initial candidate design. A breakdown of material contribution is included in Table 1.

5.3. Minimisation of Overall Weight of the Composite Beam—Objective Function 3

For this objective function, the span length and bay spacing were assumed the same as the initial candidate design. Consequently, as the floor area remained the same, the quantity of profiled decking and shear connectors remained the same. As the UB section was minimised in objective function 1, and the concrete slab depth was reduced in objective function 2, for this assessment a 203 × 102 × 23 UB with a 110 mm slab was utilised. Running these respective inputs through the structural design script, the structure passed ULS and SLS criteria and returned a total initial embodied energy of 21408.5 MJ for the structure; a reduction of 8.9% compared to the initial candidate design. A breakdown of material contribution is included in Table 1.

5.4. Maximisation of the Span Length of the Composite Beam—Objective Function 4

Building on the reduction of total initial embodied energy from objective functions 1–3, this objective function seeks to maximise the span length for the reduced UB section and concrete slab depth. The output $M_{pl,Rd}$ of objective function 3 was calculated at 155.7 kNm, with a F_d of 2076kN imposed on the entire floor area. Rearranging Equation (1) gave a theoretical span length of 7.832 m for a 203 × 102 × 23 UB with a 110 mm concrete slab over a bay spacing of 3.0 m. However, running these inputs through the structural design script, the design failed both the ULS and the SLS criteria. Manually cycling through sections to ensure these criteria were met returned a design with a 254 × 102 × 28 UB. This returned a total initial embodied energy content of 29,410.9 MJ, a 25.2% increase for a 30.4% increase in span, and a proportionally 5.4% increase in total initial embodied energy, assuming a 30.4% increase of 21,408.5 MJ = 27,916.1 MJ.

Table 1. Embodied energy quantity outputs for objective functions.

Objective Function	UB Section	Slab Depth (mm)	Span (m)	EE_a (MJ)	EE_{sc} (MJ)	EE_{ps} (MJ)	EE_c (MJ)	EE_r (MJ)	EE_{total} (MJ)
Initial Candidate Design	305 × 102 × 28	130	6.0	6226.6	293.0	8143.0	4795.2	4035.8	23,493.6
Minimised Universal Beam Section	203 × 102 × 23	130	6.0	5100.5	293.0	8143.0	4795.2	4035.8	22,367.5
Minimised Depth of Concrete Slab	305 × 102 × 28	110	6.0	6226.6	293.0	8143.0	3836.2	4035.8	22,534.6
Minimised Weight	203 × 102 × 23	110	6.0	5100.5	293.0	8143.0	3836.2	4035.8	21,408.5
Maximised Span Length	254 × 102 × 28	110	7.823	8147.2	383.9	10617.0	5001.7	5262.1	29,410.9
Minimised Deflection	203 × 133 × 25	110	6.0	5542.1	293.0	8143.0	3836.2	4035.8	21,849.2

5.5. Minimisation of the Deflection of the Composite Beam—Objective Function 5

Returning to a 6m span as per the initial candidate design, in accordance with Equation (47), the maximum deflection for SLS was limited to 24 mm. As calculated by the structural design formulae and the life cycle environmental assessment (LCEA) script, objective function 3, with the lightest components, δ_{total} was returned as 17.4 mm. Running the structural design and LCEA script with the next largest UB section found in the blue book [36] a 203 × 133 × 25, returned a deflection of 16.5 mm, however it also returned a total initial embodied energy content of 21,849.2 MJ, a 2.1% increase when compared to objective function 3. A breakdown of material contribution is included in Table 1.

6. Concluding Remarks

In this study, a MATLAB script has been produced to enable the verification of the ULS and SLS of a steel-concrete composite beam in accordance with Eurocode 4 (parts 1–3) [24]. Additionally, LCEA is included to determine the total initial embodied energy content of the beams verified by parts 1–3 of the script. This enabled the GA optimiser from the MATLAB Global Optimisation Toolbox to be implemented for optimising five objective functions.

Initially, this MATLAB script was used to run an analysis on a typical steel-concrete composite beam. The purpose of this initial candidate design was to establish benchmark conditions for structural performance in terms of ULS and SLS, and for embodied energy quantification. These benchmark values served as parameters to begin the optimisation process, and also outputs for the optimised objective functions to be compared against.

Objective function 1 had the aim to minimise the UB section of the composite beam. By implementing the MATLAB script in conjunction with the GA optimiser, it was possible to reduce the UB section, by reducing the depth of the section ha. Numerically, the output returned was accurate to the design process, but had a minimum value signification smaller than the shallowest UB section readily available; not a representative section. This required manual intervention to determine the smallest UB section that satisfied all ULS and SLS criteria. Regardless, an overall reduction in the total initial embodied energy of 4.8% was achieved. Moving forward, further refinement of the scripting is required to automate the selection of suitable UB sections.

Objective function 2 had the aim to reduce the depth of the concrete slab. Like objective function 1, it was possible to use the MATLAB script and GA optimiser to reduce the depth of the slab while numerically staying true to the structural design process. However, as the output returned effectively eliminated any depth of the slab, further refinement to the scripting is required to ensure a minimum depth is achieved within practical limits. Assuming the shallowest practical depth of the slab, the total initial embodied energy can be reduced by 4.1%.

To reduce overall weight for objective function 3, a combination of the results of objective functions 1 and 2 and consistent beam span/spacing as the initial candidate design were used. It was possible to determine a design that achieved a reduction of 8.9% of total initial embodied energy whilst satisfying all ULS and SLS criteria.

Building upon the outputs of objective functions 1–3, objective function 4 aimed to maximise the span length of the composite beam. Adjusting Equation (1), it gave a theoretical maximum length. When proportionally comparing the energy content of the objective function 3 design, and design for objective function 4, a 5.4% increase in total initial embodied energy was returned. This is a result of the overall increase in material quantity.

For objective function 5, again the combination of reduced UB section and slab depth resulted in the best performer for satisfying ULS and SLS criteria as well as minimised energy content. However, it was shown that increasing the UB section in an attempt to reduce the overall deflection returned a predictable increase in energy content, in this instance as a 2.1% increase against the initial candidate design.

In summary, these objective functions have been applied to a simply supported steel-concrete composite beam, with the best design selected from the lowest resultant initial embodied energy. Objective functions 1–3 and 5 return a reduction in the initial embodied energy. For objective function 4, an increased span length naturally increases the initial embodied energy. For more complex structures, such as a structural grid or a complete floor plate, otherwise for an analysis including more components and/or supporting members, it is envisaged that this increased complexity will introduce a greater degree of variety on the design parameters and subsequent outputs. Therefore, it is recommending that all objective functions are implemented to assess which scenario returns the minimal initial embodied energy value. In addition, it is suggested that the available steel sections are introduced into the MATLAB tool, and create an automated selection based on the values returned from the objectives all together, to assist practising engineers with quick results.

Author Contributions: Both authors have contributed equally to the work. A.H.W. was supervised by K.D.T. during his research studies in the School of Civil Engineering at the University of Leeds. The background work has been carried out by both authors, the computational work was conducted by the first author and supervised by the second one. Both authors have contributed to the writing of the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Engineering and Physical Sciences Research Council in the UK (EP/L504993/1).

Acknowledgments: This work is part of a larger research project on dealing with the utilisation of optimisation algorithms to optimise steel-concrete composite structures in terms of their embodied energy demand. The authors would like to thank the sponsors of this research work, the Engineering and Physical Sciences Research Council (EP/L504993/1) for the financial support and WSP London for both their financial and technical support.

Conflicts of Interest: There are no conflicts of interest to declare.

Nomenclature

GA	Genetic Algorithm
UB	Universal Beam
ULS	Ultimate Limit State
SLS	Serviceability Limit State
M_{Ed}	Design Bending Moment
V_{Ed}	Design Shear Force
g_k	Permanent Action
q_k	Variable Action
γ_g	Partial Factor of Safety for Permanent Actions
γ_q	Partial Factor of Safety for Permanent Actions
γ_{M0}	Partial Factor for Resistance–Structural Steel
γ_c	Partial Factor for Resistance–Concrete
γ_s	Partial Factor for Resistance–Reinforcing Steel
γ_v	Partial Factor for Resistance–Shear Connectors
F_d	Combined Actions
h_a	Depth of Universal Beam
b_a	Width of Universal Beam

d	Depth Between Fillets
t_w	Web Thickness
t_f	Flange Thickness
r	Radius of Root Fillet
A_a	Area of Universal Beam
$W_{pl,y}$	Universal Beam Plastic Modulus (y-y axis)
I_{yy}	Universal Beam Second Moment of Area (y-y axis)
I_a	Universal Beam Second Moment of Area (dominant axis)
L	Beam Span
S	Beam Spacing
d_{slab}	Depth of Slab
h_c	Height of Concrete Above Profile
h_p	Height of Profiled Deck
b_1	Width of Bottom Trough
b_2	Width of Top Trough
$\varnothing$	Nominal Diameter of Shear Connector
h_{sc}	Height of Shear Connector prior to Welding
F_y	Yield Strength of Structural Steel
F_u	Ultimate Strength of Structural Steel
F_{yk}	Yield Strength of Reinforcing Steel
F_{ck}	Cylinder Strength of Concrete
E_{cm}	Secant Modulus of Elasticity
b_{eff}	Effective Width of the Compression Flange
$N_{c,slab}$	Compression Resistance of the Concrete Slab
N_{pla}	Tensile Resistance of the Steel Section
$M_{pl,Rd}$	Moment Capacity for Full Shear Connection
P_{Rd}	Design Shear Resistance of a Single Shear Connector
k_t	Deck Shape Influence Factor
$M_{pl,a,Rd}$	Plastic Moment Resistance of the Universal Beam
M_{Rd}	Moment Capacity for Partial Shear Connection
$V_{pl,Rd}$	Vertical Shear Resistance of the Composite Beam
A_v	Area of Shear
A_{sf}	Cross Sectional Area of Reinforcing Steel
F_{yd}	Yield Strength of Reinforcing Steel
ε_{cs}	Total Shrinkage Strain
ε_{cd}	Drying Shrinkage Strain
ε_{ca}	Autogenous Shrinkage Strain
$f_{cm(t)}$	Minimum Concrete Strength for Time (t)
RH	Relative Humidity
E_L	Effective Modulus of Elasticity of Concrete
E_0	Short Term Effective Modulus of Elasticity of Concrete
E_p	Permanent Effective Modulus of Elasticity of Concrete
E_s	Effective Modulus of Elasticity of Concrete for Shrinkage
I_c	Second Moment of Area of Concrete Flange
EI_L	Effective Flexural Stiffness of Concrete Flange
EI_0	Short Term Effective Flexural Stiffness of Concrete Flange
EI_p	Permanent Effective Flexural Stiffness of Concrete Flange
EI_s	Effective Flexural Stiffness of Concrete Flange for Shrinkage
$\Phi_{(t,t0)}$	Creep Coefficient
δ_i	ith Deflection Component
δ_{total}	Total Deflection
e_d	Combined Actions for Serviceability Limit State
a_c	Distance Between Centroidal Axes of Concrete Flange and Universal Beam
EE_i	Initial Embodied Energy Content of Steel-Concrete Composite Beam
EE_{total}	Total Initial Embodied Energy Content of Steel-Concrete Composite Beam
EE_a	Initial Embodied Energy Content of Universal Beam
EE_{sc}	Initial Embodied Energy Content of Shear Connectors

EE_{ps}	Initial Embodied Energy Content of Profiled Deck
EE_c	Initial Embodied Energy Content of Concrete Slab
EE_r	Initial Embodied Energy Content of Reinforcing Steel
m_i	Quantity of Material (i)
M_i	Cradle to Gate Embodied Energy Content for Material (i)
E_c	Embodied Energy Content for Construction Activities

References

1. Ahmed, I.; Tsavdaridis, K.D.; Neysari, F. A new breed of sustainable ultra-lightweight and ultra-shallow steel-concrete composite flflooring system: Life cycle assessment (LCA) of materials. In Proceedings of the International Conference Coordinating Engineering for Sustainability and Resilience (CESARE 2017), Dead Sea, Jordan, 3–8 May 2017; pp. 3–8.
2. Ahmed, I.; Tsavdaridis, K.D.; Neysari, F. Push-out shear tests for a novel pre-fabricated shallow steel-concrete composite flflooring system. In Proceedings of the 12th International Conference on Advances in Steel-Concrete Composite Structures (ASCCS 2018), Valencia, Spain, 27–29 June 2018; pp. 27–29.
3. Ahmed, I.; Tsavdaridis, K.D. Prefabricated Composite Flooring Systems with Normal and Lightweight Concretes. In Proceedings of the The 14th Nordic Steel Construction Conference (NSCC 2019), In Special Issue Proceedings of Nordic Steel, (DTU), Copenhagen, Denmark, 18–20 September 2019; Volume 3, pp. 257–263.
4. Ahmed, I.M.; Tsavdaridis, K.D. Life Cycle Assessment (LCA) Study of European Lightweight Composite Flooring Systems. *J. Build. Eng.* **2018**, *20*, 624–633. [CrossRef]
5. Ahmed, I.M.; Tsavdaridis, K.D. The Evolution of Composite Flooring Systems: Applications, Testing, Modelling and Eurocode Design Approaches. *J. Constr. Steel Res.* **2019**, *155*, 286–300. [CrossRef]
6. Tsavdaridis, K.D.; D'Mello, C. Finite Element Investigation of Perforated Beams with Different Web Opening Configurations. In Proceedings of the The 6th International Conference on Advances is Steel Structures (ICASS 2009), Hong Kong, China, 16–18 December 2009; pp. 213–220.
7. Tsavdaridis, K.D.; D'Mello, C.; Hawes, M. Experimental Study of Ultra Shallow Floor Beams (USFB) with Perforated Steel Sections. In Proceedings of the The 11th Nordic Steel Construction Conference 2009 (NSCC 2009), Malmö, Sweden, 2–4 September 2009; Volume 128, pp. 312–319.
8. Tsavdaridis, K.D.; D'Mello, C.; Huo, B.Y. Experimental and Computational Study of Vertical Shear Behaviour of Partially Encased Perforated Steel Beams. *Eng. Struct.* **2013**, *56*, 805–822. [CrossRef]
9. Tsavdaridis, K.D.; Galiatsatos, G. Assessment of Cellular Beams with Transverse Stiffeners and Closely Spaced Web Openings. *Thin Walled Struct.* **2015**, *94*, 636–650. [CrossRef]
10. Demetriou, D.; Nikitas, N.; Tsavdaridis, K.D. Performance of Fixed-Parameter Control Algorithms on High-Rise Structures Equipped with Semi-Active Tuned Mass Dampers. *Struct. Des. Tall Spec. Build.* **2015**, *25*, 340–354. [CrossRef]
11. Demetriou, D.; Nikitas, N.; Tsavdaridis, K.D. Semi Active Tuned Mass Dampers of Buildings: A Simple Control Option. *Am. J. Eng. Appl. Sci. Spec. Issue Struct. Eng.* **2015**, *8*, 620–632. [CrossRef]
12. Tsavdaridis, K.D.; D'Mello, C. Optimisation of Novel Elliptically-Based Web Opening Shapes of Perforated Steel Beams. *J. Constr. Steel Res.* **2012**, *76*, 39–53. [CrossRef]
13. Tsavdaridis, K.D.; Kingman, J.J.; Toropov, V.V. Application of Structural Topology Optimisation to Perforated Steel Beams. *Comput. Struct.* **2015**, *158*, 108–123. [CrossRef]
14. Kingman, J.J.; Tsavdaridis, K.D.; Toropov, V.V. Applications of Topology Optimisation in Structural Engineering: High-rise Buildings & Steel Components. *Jordan J. Civ. Eng.* **2015**, *9*, 335–357.
15. Hawdon-Earl, S.; Tsavdaridis, K.D. Form Finding and Dimensioning of Reinforced Concrete Shell Roof for Akrotiri (Santorini). *J. Int. Assoc. Shell Spat. Struct. (IASS)* **2018**, *59*, 198.
16. Fraser, A.S. Simulation of Genetic Systems by Automatic Digital Computers. *Aust. J. Biol. Sci.* **1957**, *10*, 484–491. [CrossRef]
17. Panchal, D.R. Steel-Concrete Composite Beam Design Using Genetic Algorithms. *Int. J. Innov. Res. Dev.* **2014**, *3*, 473–480.
18. Alanka, K.; Chaudhary, S. Cost Optimisation of Composite Beams using Genetic Algorithm and Artificial Neural Network. In Proceedings of the 2012 International Conference on Computer Technology and Science (ICCTS), New Delhi, India, 18–19 August 2012.

19. Senouci, A.B.; Al-Ansari, M.S. Cost Optimisation of Composite Beams using Genetic Algorithms. In *Advances in Engineering Software*; Elsevier: Amsterdam, The Netherlands, 2009; Volume 40, pp. 1112–1118.
20. Artar, M.; Daloglu, A.T. Optimum Design of Composite Steel Frames with Semi-Rigid Connections and Column Bases via Genetic Algorithm. *Steel Compos. Struct.* **2015**, *19*, 1035–1053. [CrossRef]
21. Eleftheriadis, S.; Dunant, C.F.; Drewniok, M.P.; Rogers-Tizard, W. A Computational Paradigm for the Optimisation of Steel Building Structures Based on Cost and Carbon Indexes in Early Design Stages. In Proceedings of the 24th International Workshop on Intelligent Computing in Engineering (EG-ICE-2017), University of Nottingham, Nottingham, UK, 10–12 July 2017.
22. Eleftheriadis, S.; Dunant, C.F.; Drewniok, M.P.; Rogers-Tizard, W.; Kyprianou, C. Comparative Numerical Analysis for Cost and Embodied Carbon Optimisation of Steel Building Structures. *Adv. Comput. Des.* **2018**, *3*, 385–404.
23. MathWorks. *Global Optimisation Toolbox Version R2019A.S.I:S.N*; 2019.
24. CEN. European Committee for Standardisation. In *Eurocode 4: Design of Steel and Concrete Composite Structures Part 1-1: General Rules and Rules for Buildings*; CEN: Brussels, Belgium, 2005.
25. Mitchell, M. *An Introduction to Genetic Algorithms*; First MIT paperback, Ed.; Massachusetts Institute of Technology: Cambridge, MA, USA, 1996.
26. CEN European Committee for Standardisation. *Eurocode 1 Actions on Structures-Part 1-1: General Actions-Densities, Self-Weight, Imposed Loads for Buildings*; European Committee for Standardisation: Brussels, Belgium, 2002.
27. CEN European Committee for Standardisation. *Eurocode: Basis of Structural Design*; European Committee for Standardisation: Brussels, Belgium, 2002.
28. British Standards Institute. UK National Annex to Eurocode 1. Actions on Structures. In *General Actions-Densities, Self-Weight, Imposed Loads for Buildings*; British Standards Institute: London, UK, 2005.
29. CEN. European Committee for Standardisation. In *Eurocode 3: Design of Steel Structures-Part 1-1: General Rules and Rules for Buildings*; CEN: Brussels, Belgium, 2006.
30. CEN. European Committee for Standardisation. In *Eurocode 2: Design of Concrete Structures-Part 1-1: General Rules and Rules for Buildings*; CEN: Brussels, Belgium, 2004.
31. Heaton Products LTD. 2019. Reinforcement Mesh. Available online: https://www.heatonproducts.co.uk/products/reinforcement-mesh/ (accessed on 27 April 2019).
32. Ramesh, T.; Prakesh, R.; Shukla, K.K. Life cycle Energy Analysis of Buildings: An Overview. Elsevier. *Energy Build.* **2010**, *42*, 1592–1600. [CrossRef]
33. Hammond, G.P.; Jones, C.I. *Inventory of Carbon and Energy (ICE)*; University of Bath: Bath, UK, 2008.
34. Tata Steel. *ComFlor® Manual Composite Floor Decking Design and Technical Manual*; Tata Steel UK Limited: London, UK, 2017.
35. SMD. *Best Practice Data Sheet DATA/11 SMD Shear Studs SMD.DAT.152.V4*; SMD Stockyards Limited; Available online: http://smdltd.co.uk/wp-content/uploads/2016/06/SMD.DAT_.152.V4-Best-Practice-Data-Sheet-DATA.11-SMD-Shear-Studs.pdf (accessed on 12 April 2020).
36. Steel Construction Info. Universal Beams Interactive 'Blue Book'. Available online: https://www.steelforlifebluebook.co.uk/ub/ec3-ukna/section-properties-dimensions-properties/ (accessed on 1 May 2019).